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# Aquaculture Production is a Large, Spatially Concentrated Source of Nutrients in Chinese Freshwater and Coastal Seas

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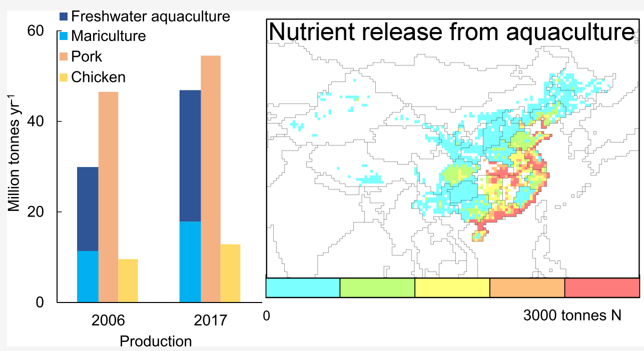
*Supporting Information*

**ABSTRACT:** As Chinese aquaculture production accounts for over half of the global aquaculture production and has increased by 50% since 2006, there is growing concern about eutrophication caused by aquaculture in China. This paper presents a model-based estimate of nutrient flows in China's aquaculture system during 2006−2017 using provincial scale data, to spatially distribute nutrient loads with a 0.5° resolution. The results indicate that with the increase in fish and shellfish production from 30 to 47 million tonnes (Mt) during 2006−2017, the nitrogen (N) release increased from 1.0 to 1.6 Mt/year and that of phosphorus (P) from 0.1 to 0.2 Mt/year. Nutrient release from freshwater aquaculture was concentrated in Guangdong, Jiangsu, and Hubei, and that from mariculture in Shandong, Fujian, and Guangdong. Aquaculture is an important strongly concentrated nutrient source in both freshwater and marine environments. Its nutrient release is >20% of total nutrient inputs to freshwater environments in some provinces, and nutrients from mariculture are comparable to river nutrient export to Chinese coastal seas. Aquaculture production and nutrient excretions are now comparable to those of livestock production systems in China and need to be accounted for when analyzing causes of eutrophication and harmful algal blooms and possible mitigation strategies.




## 1. INTRODUCTION

Annual global aquaculture production has increased from <1 million tonnes (Mt) in 1950 to 112 Mt in 2017.[1] The aquaculture production in Asia reached 103 Mt per year in 2017, accounting for approximately 92% of the global production, and >60% of Asian aquaculture production was in China.[1] China's aquaculture production has been increasing since 1950, but with accelerated growth since 1980[2] (Figure 1). China's capture fishery production has been stagnant since a few decades,[1] and aquaculture has filled the growing gap between the rapidly increasing demand for fish protein and the constant supply from capture fishery (Figure 1).[3] Between 1961 and 2013, the consumption of finfish and shellfish in China increased from 4 to 35 kg/capita/year,[4] and the consumption of meat from 3 to 60 kg/capita/year in 2013.[4] Aquaculture is, therefore, an essential source of animal protein for the booming population,[5] as it contributes >80% to China's total fish production (Figure 1).[1]

There is increasing concern about the negative effects of nutrients released by aquaculture to aquatic ecosystems.[6−8] The main inputs in aquaculture systems are feed and seston, which are transformed to fish biomass or released to the surface water as feed wastes and excreta in the form of suspended organic solids or dissolved nutrients, including

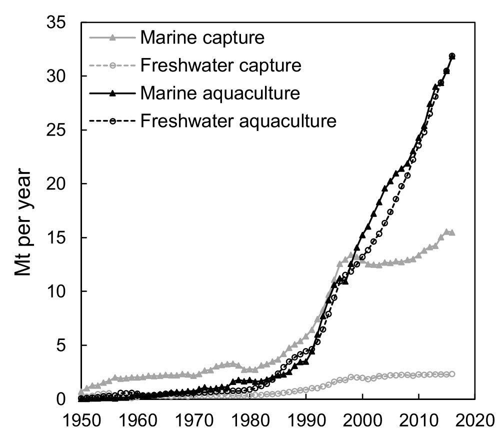



**Figure 1.** Marine and freshwater capture and aquaculture production in China for 1950−2016. Production data are from FAO.[2] Brackish water production is included in marine production. Data for Taiwan are not included in the aquaculture production data.

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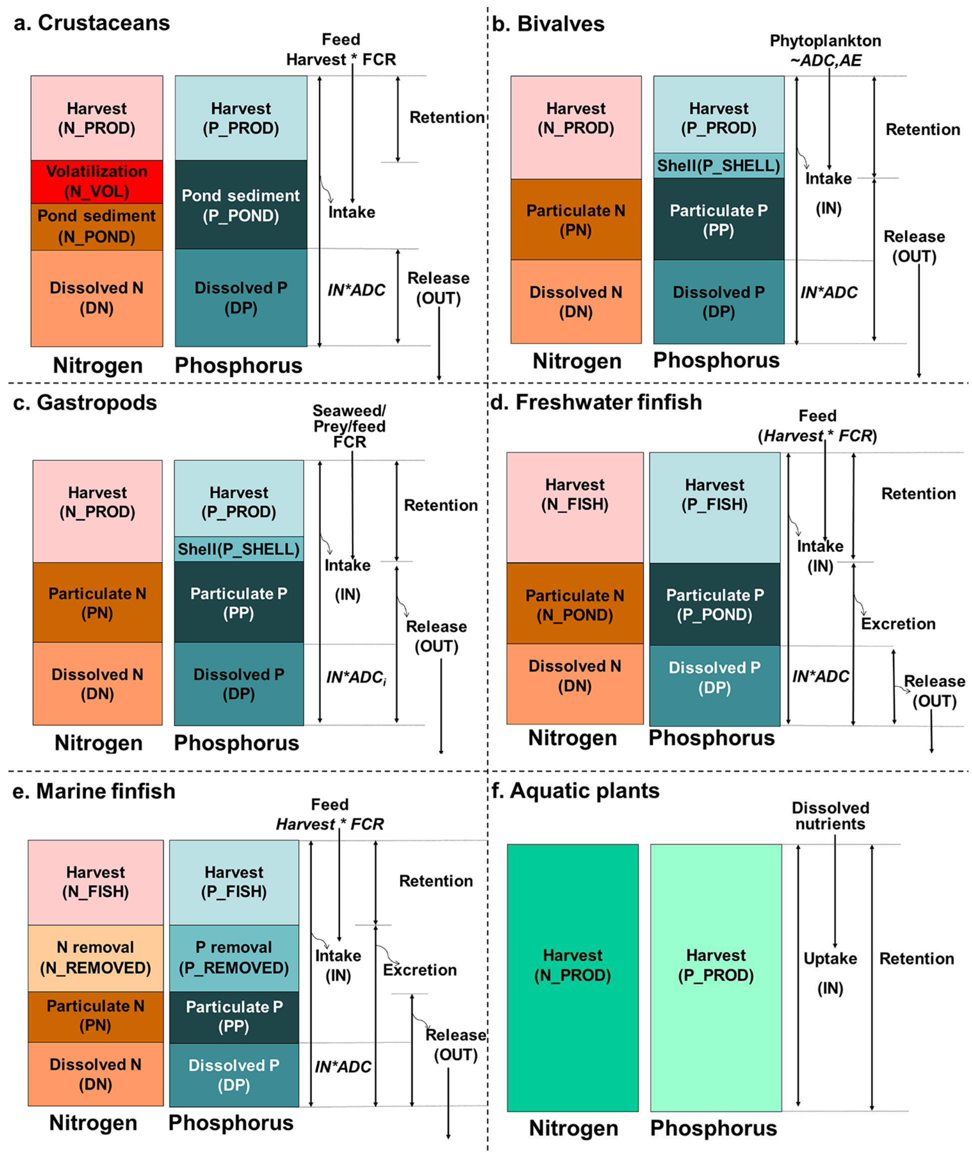


**Figure 2.** Scheme of the Integrated Model to Assess the Global Environment (IMAGE)−Global Nutrient Model (GNM) aquaculture nutrient budget model for (a) crustaceans, (b) bivalves, (c) gastropods, (d) freshwater finfish, (e) marine finfish, and (f) aquatic plants. For each species group, the feed nutrient intake, nutrient retention (in harvested fish), and nutrient release are shown. Feed nutrient intake is determined by the feed conversion ratio (FCR) or the apparent digestibility coefficient (ADC) and assimilation efficiency (AE) for bivalves. Nutrient release consists of dissolved and particulate N and P forms. The ADC determines the fraction of feed nutrient intake that is excreted as dissolved nutrients; the excretion of particulate nutrients is calculated as the difference between total nutrient intake, the nutrient retention, and the excretion of dissolved nutrients. Nitrogen from shrimp ponds can volatilize as ammonia (a). The nutrients from freshwater finfish pond systems can be recycled (d). Dissolved nutrients from marine finfish can be taken up by other species in integrated aquaculture systems (e), where this is relevant. (a), (b), and (f) are modified from Bouwman et al.;[6] (c), (d), and (e) are modified from Bouwman et al.[7,27]

nitrogen (N) and phosphorus (P).[9,10] In intensive aquaculture systems such as cage and pond cultures, waste generated in excess of the assimilative capacity is often discharged without treatment.[9] Dissolved inorganic nutrients such as ammonia, urea, and phosphate produced by aquaculture can be readily taken up by phytoplankton and macroalgae and stimulate their growth.[10−12] This enhanced production often leads to hypoxia and harmful algal blooms (HABs).[8,10,12−14] Nutrient proportions (e.g., N/P ratios) and forms (e.g., ammonium, nitrate, or urea) are important factors causing the proliferation of HABs.[15] Aquaculture is not only a source of nutrients that contribute to HAB formation, but it can also be a victim of HABs with large economic damage.[8,10,14,16−19] China's mariculture area increased from 4000 $km^2$ in 1954 to 83 000 $km^2$ in 2017, and the annual HAB frequency in China's coastal environments also increased rapidly between the 1950s and 2017.[20−22] Similarly, with the development of China's freshwater aquaculture, the annual frequency and duration of HABs in inland waters, such as Taihu Lake, have increased rapidly since the 1980s.[23,24] The HAB problem seems to increase, with increasing frequency and extent in an increasing number of locations, with more toxins.[15]

Quantitative estimates of nutrient release from aquaculture in China are scarce. The annual release of total N and P from China's aquaculture into aquatic ecosystems was estimated on the basis of provincial aquaculture production data statistics and nutrient enrichment of water and sediments in aquaculture sites.[5] Recent global estimations[6,7] were based on a nutrient


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budget model using national aquaculture production data by species group from FAO[25,26] to calculate country estimates of nutrient loads from aquaculture for different forms of nutrients (particulate and dissolved N and P). Using the same aquaculture nutrient budget model, and provincial data, the nutrient release from mariculture was compared to river export.[27]

To analyze the impact of nutrient release by aquaculture production, we need to know the spatiotemporal distribution of nutrient loading and nutrient proportions and forms. This will allow us to compare nutrient delivery to surface water with other sources of nutrients, such as wastewater. In this study, we apply the above nutrient budget model for aquaculture[6,7] in combination with detailed provincial data to analyze the within-province spatiotemporal distribution of production and nutrient release for freshwater, brackish water, and marine aquaculture. This paper has online Supporting Information (SI). The model output is available on request from the corresponding author.

## 2. MATERIALS AND METHODS

**2.1. Overall Approach.** We employ a nutrient budget model that describes the major flows of nutrients in aquaculture systems. This model is part of the Integrated Model to Assess the Global Environment (IMAGE)−Global Nutrient Model (GNM). The model describes N and P in (i) feed inputs, (ii) fish production, (iii) excretion in the form of particulate and dissolved nutrients, and (iv) the fate of the nutrients (release, retention in pond sediment, recycling or removal by algae in integrated aquaculture systems (Figure 2)). Individual species within crustaceans, seaweed, fish, and mollusks are aggregated to the International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) groups,[1] for which production characteristics are specified. For presenting our results, the ISSCAAP groups are aggregated further to two groups of finfish (i.e., carnivores and omnivores), filter-feeding bivalve mollusks (hereafter referred to as bivalves), crustaceans, gastropods (mainly abalone, Chinese mystery snail, and other snails), and aquatic plants. Table S1 in the SI lists the ISSCAAP groups and the individual species included in each group for freshwater and marine environments. In Section 2.2, we will discuss the data, and Section 2.3 provides a model summary. A detailed model description has been provided in detail elsewhere.[6,7,27]

**2.2. Data Description.** Provincial aquaculture production data for the period 2006−2017 (i.e., 2006, 2010, 2015, 2016, and 2017; see Table S2) were obtained from the China Fishery Statistical Yearbook.[28] The annual production is provided per province, species, aquaculture area, and type of environment. The production data on finfish, crustaceans, gastropods, and mollusks are expressed in units of live weight (i.e., market size weight, including shell and skeleton). Because the production data for aquatic plants are expressed in dry weight, we multiplied the production of Japanese kelp by 5 and that of all of the other aquatic plant groups by 10 to match the FAO statistics (i.e., in wet weight).[1,2] We observed a number of discrepancies between Chinese statistics and FAO data. The way in which we handled these differences is discussed in Table S3.

**2.3. Model Description.** The different budget terms distinguished in the model are indicated in Figure 2. Below we will describe the model in broad terms for nutrient and feed intake, nutrients in the harvested fish, and nutrient release and management. Model parameters for the ISSCAAP groups are region-specific, and in the case of China, country-specific.

For estimating total feed and nutrients used in the production of finfish, crustaceans, and gastropods, the model uses the concept of feed conversion ratio (FCR) (Figure 2a−e), i.e., the amount of feed or food required to produce 1 kg of body weight. FCR values decline when efficiencies increase and feed losses are minimized, as observed in many fed aquaculture systems. Nutrient intake is estimated using N and P contents of the feed. The model for filter-feeding bivalves uses N and P conversion ratios (NCR and PCR), inferred from the assimilation efficiencies for N and P and the fractions of dissolved N and P in the excretion (apparent digestibility coefficient, ADC) (Figure 2b).

For shrimps and carnivore and omnivore finfish species, the model uses feed rations (diets) consisting of three broad types of fish feed with different FCRs and nutrient compositions: (i) compound feed, usually industrially manufactured; (ii) non-compound feed, consisting of locally available feeds; and (iii) "natural" feed is natural production of aquatic plants typical for extensive production systems with omnivorous species such as carp and tilapia. Rations are not constant in time. Carnivore finfish rations rely on types (i) and (ii), and omnivore finfish rations increasingly include compound and other feeds.

Nutrient retention is calculated from the production data (i.e., harvest) and nutrient content of the various fish and shellfish groups; for shellfish, the harvested parts consist of the shell and meat, both with different nutrient contents (Figure 2a−e).

The difference between intake and retention in the fish is the nutrient release. Part of this is in dissolved form, and the remainder is in particulate form (feces and feed losses; and both feces and pseudofaeces in the case of bivalves). The fractions of dissolved nutrients are calculated from the apparent digestibility coefficients (ADC) for protein and P in the feed (Figure 2). Nutrient release to surface water from shrimp ponds is the excretion minus ammonia volatilization and denitrification losses (Figure 2a). However, ammonia and denitrification losses were ignored for fish ponds (Figure 2d,e) because of (i) insignificant ammonia volatilization at pH < 7.5; (ii) anerobic conditions in pond sediment leading to a near absence of nitrification, and thus low denitrification rates. Part of the nutrients from ponds are assumed to be recycled as fertilizers in agriculture. All nutrients excreted in cages and feed losses are assumed to be released to the aquatic environment. Where relevant, nutrients released by finfish are recycled in integrated aquaculture systems (e.g., by shellfish or aquatic plants) or removed by wastewater treatment (Figure 2d,e).

**2.4. Allocation of Nutrient Release from Aquaculture.** For distributing the aquaculture production spatially within the Chinese provinces, an allocation procedure based on a weighing factor map was developed to estimate the "attractiveness" for freshwater, brackish water, and marine aquaculture at 0.5 × 0.5° resolution.

*2.4.1. Freshwater Aquaculture.* The attractiveness for freshwater aquaculture production was made based on a combination of population density, type of freshwater bodies, and temperature. The weighing factors ($W_{population}$, $W_{temp}$, and $W_{waterbody}$; no dim) range from 0 (not attractive for aquaculture production) to an arbitrary maximum value (highly attractive).

For population density, all grid cells with no inhabitants and those with more than 10 000 inhabitants/km$^2$ were excluded; the highest attractiveness was assumed for an optimum density


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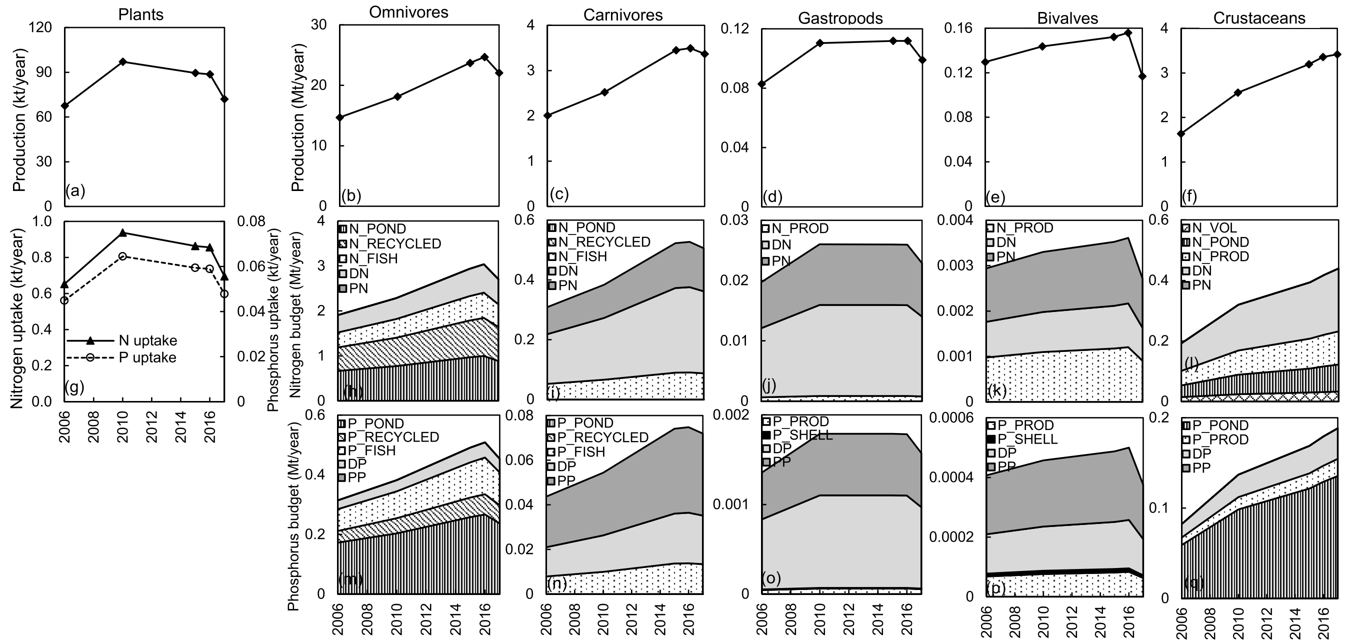


**Figure 3.** Aquatic plant, finfish, and shellfish aquaculture production and associated nutrient budgets in Chinese freshwater aquaculture production during 2006−2017. (a−f) Production for (a) plants, (b) omnivorous finfish, (c) carnivorous finfish, (d) gastropods, (e) bivalves, and (f) crustaceans. Nutrient budgets: (g) N and P uptake by aquatic plants; (h−l) N budgets for (h) omnivores, (i) carnivores, (j) gastropods, (k) bivalves, and (l) crustaceans; (m−q) P budgets for (m) omnivores, (n) carnivores, (o) gastropods, (p) bivalves, and (q) crustaceans. Production data for China Mainland are from China Fishery Statistical Yearbook.[28] Provincial total production data and the nutrient budgets (N in feed, harvest and N and P release to surface waters) are in Table S5. Data for Taiwan are not included in the aquaculture production data.

of 1000 inhabitants/km$^2$, according to a steep parabolic function for densities lower than the optimum and less steep for densities >1000 inhabitants/km$^2$

$$W_{\text{population}} = ax^2 + bx + c \quad (1)$$

where $x$ = population density. The values of $a$, $b$, and $c$ depend on the population density (see Section 5 in the SI (pp S9−S10)). The attractiveness for freshwater aquaculture furthermore depends on the type of water body. We use the 12 water body types distinguished in the Global Lakes and Wetlands Database (GLWD)[29] (Table S4). Lacking water temperature data, we use mean annual air temperature as a proxy. Considering that aquaculture does not occur in cold regions, we assume that $W_{\text{temperature}} = 0$ for annual temperature ≤0 °C and $W_{\text{temperature}} = 1$ for annual temperature >0 °C.

The overall attractiveness for aquaculture within a grid cell is calculated as follows

$$W = W_{\text{population}} W_{\text{waterbody}} W_{\text{temperature}} \quad (2)$$

The population density and water temperature for 2000 were used for all years; thus, the weighing factor $W$ is constant in time. All grid cells with a probability $W$ < 10% of the maximum in that province are set to zero. Aquaculture production and all budget terms including nutrient release are allocated to the remaining grid cells based on the ratio of the $W$ of the grid cell considered and the sum of $W$ of all grid cells within that province. Subsequently, all grid cells with a production <1000 kg are excluded by setting $W$ = 0 for these cells, and the allocation procedure is repeated. Details on this procedure are provided in Section 5 in the SI.

*2.4.2. Brackish and Marine Aquaculture.* Nutrients released by brackish water aquaculture production are allocated to coastal grid cells (a one-cell strip of land grid cells bordering the sea) following the allocation procedure for freshwater aquaculture. Nutrient release from marine aquaculture is allocated to a one-cell strip of sea grid cells bordering coastal land cells. We use three weighing factors, i.e., coastline length, coastal type, and temperature. Coastline length (from ArcGIS) is a proxy for the presence of bays or other coastal waters partly sheltered from the influence of the open sea. In addition, aquaculture production is allocated preferentially in specific coastal types.[30] Tidal systems (estuaries, rias, and embayments), fjords, and fjaerds are assigned a weighing factor of 10, small deltas a weighing factor of 5, and all other coastal types (endorheic or glaciated, lagoons, large rivers bypassing the near-shore coastal zone, large rivers with tidal deltas, karst, and arrheic coasts) have a weighing factor of 1. Finally, temperature is used as a weighing factor following the procedure for freshwater aquaculture allocation. During the allocation procedure, the weighing factor is set to 0 for grid cells with production <1000 kg/year, and the allocation procedure is repeated.

## 3. RESULTS

**3.1. Production and Nutrient Budget for Freshwater Aquaculture.** Freshwater production increased from 19 Mt in 2006 to 32 Mt in 2016, slightly decreased to 29 Mt in 2017 (increase rate of 1.0 Mt/year), and made up about 47% of total Chinese aquaculture production. Freshwater plants accounted for <1% of the total freshwater aquaculture production during 2006−2017 (Figure 3). Annual N and P in feed were approximately 2.4 and 0.4 Mt in 2006, respectively, and reached the maximum of 4.0 Mt of N and 0.8 Mt of P in 2016, and 3.7 Mt of N and 0.7 Mt of P in 2017 (Figure 3; Table S5). Approximately 18−19% of N and 9−15% of P in feed were retained in the harvest, while the N released to surface water was 31−33% of the feed N intake, and the feed P release 19−



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20% of the P intake over the period 2006−2017. The N release increased from 0.8 Mt in 2006 to 1.3 Mt in 2016 and declined slightly in 2017; the P release increased from 0.08 to 0.15 Mt between 2006 and 2016 and declined slightly in 2017. The average annual N release per tonne of freshwater aquaculture production (excluding plants) was almost constant at 41−42 kg; the P release per tonne of production was 4.4−4.8 kg, with a total nitrogen to total phosphorus (TN/TP) molar ratio of about 20. Ammonia volatilization and denitrification from ponds more than doubled from 0.014 to 0.03 Mt N between 2006 and 2017.

Omnivores accounted for the largest fraction of freshwater aquaculture production with a range of 75−79% (88−89% of this is carp), and crustaceans and carnivores each accounted for approximately 10% (Figure 3; Table 1). The order of the proportions of freshwater production by groups was omnivores > carnivores > crustaceans in 2006, but the order has changed to omnivores > crustaceans > carnivores since 2010 because of the increase in the proportion of crustacean production and the decrease in the carnivore finfish production.

**Table 1. Nutrient Release from Omnivore and Carnivore Finfish, Bivalves, Crustaceans, and Gastropods for 2006 and 2017**

| | | production (Mt) | | N release (kt) | | P release (kt) | |
|---|---|---|---|---|---|---|---|
| | | 2006 | 2017 | 2006 | 2017 | 2006 | 2017 |
| type | species group | Mt/year | | kt/year | | kt/year | |
| Freshwater Aquaculture | | | | | | | |
| | omnivore finfish | 14.7 | 22.0 | 383.5 | 560.7 | 29.6 | 45.4 |
| | carnivore finfish | 2.0 | 3.4 | 256.1 | 418.6 | 35.8 | 58.5 |
| | bivalves | 0.1 | 0.1 | 2.0 | 1.8 | 0.3 | 0.3 |
| | crustaceans | 1.7 | 3.5 | 90.6 | 207.6 | 14.8 | 33.9 |
| | gastropods | 0.1 | 0.1 | 19.1 | 22.1 | 1.3 | 1.5 |
| | total | 18.6 | 29.1 | 751.2 | 1210.8 | 81.8 | 139.6 |
| Mariculture | | | | | | | |
| | omnivore finfish | 0 | 0 | 0 | 0 | 0 | 0 |
| | carnivore finfish | 0.6 | 1.4 | 71.9 | 154.6 | 11.3 | 24.6 |
| | bivalves | 9.5 | 14.2 | 73.9 | 108.5 | 11.6 | 17.0 |
| | crustaceans | 0.9 | 1.8 | 53.7 | 101.9 | 8.8 | 16.6 |
| | gastropods | 0.3 | 0.4 | 15.0 | 44.0 | 1.0 | 3.0 |
| | total | 11.3 | 17.8 | 214.5 | 409.1 | 32.7 | 61.2 |

Annual N release to surface water by freshwater finfish increased from 0.6 Mt in 2006 to 1.1 Mt in 2016 and decreased to 1.0 Mt in 2017. P release increased from 0.07 Mt in 2006 to 0.11 Mt in 2016 and 0.10 Mt in 2017 (Figure 3). The N release per tonne of finfish production was 38−39 kg, and that of P was 3.9−4.1 kg per tonne of fish. The contributions from omnivores to the total freshwater aquaculture N and P release (i.e., 57−60% for N and 44−46% for P) were lower than their contribution to production, while the contributions of carnivores to the total N and P release (i.e., 40−43% for N and 54−56% for P) were more than three times their contribution to production (i.e., 12−13%). This is due to the recycling of nutrients from ponds (e.g., carp), which does not occur in cage systems. The nutrient release per unit of production from carnivores slowly declined during 2006−2017, while that from omnivores slowly increased. The calculated molar TN/TP ratio of nutrients released from finfish was 21:1, and the corresponding ratios from omnivores and carnivores were approximately 27:1 and 16:1.

Freshwater crustaceans, bivalves, and gastropods contributed 10−13% of total freshwater aquaculture production, and 15−19% of N release and 20−26% of P release from the total freshwater aquaculture during 2006−2017. Details on their production and nutrient budgets can be found in Section 6 in the SI (pp S11).

In 2006, most of China's freshwater aquaculture production occurred in Guangdong (15%), Jiangsu (13%), and Hubei (13%), with annual production >2 Mt mostly in the Yangtze River basin and Pearl River basin (Figure 4; Table S5). In 2017, the provinces with annual production >2 Mt increased to five, i.e., Hubei, Guangdong, Jiangsu, Hunan, and Jiangxi (in decreasing order), with even >3 Mt per year in Hubei, Guangdong, and Jiangsu. Provincial distributions of N and P release were consistent with those of their production. The largest nutrient release is in Hubei, Guangdong, and Jiangsu in 2017 (Figure 4). In these provinces, omnivores and carnivores are responsible for 81% of the N release and 74% of the P release.

### 3.2. Production and Nutrient Budget for Mariculture.

China's annual aquaculture fish production in marine environments increased from 11 to 18 Mt during 2006−2017 (growth rate of 0.6 Mt/year) (Figure 5; Table 1), while the fish production in brackish environments increased from 0.7 to 1.5 Mt/year. The production of marine aquatic plants increased from 9.7 to 14.8 Mt over the same period (>100 times the production of freshwater plants) (Figure 5).

Annual N and P in feed for mariculture fish were approximately 0.3 and 0.01 Mt in 2006, respectively, which was only 14−18% of the annual feed nutrients in freshwater aquaculture (Figure 5). However, the feed input of N and P in mariculture feed almost doubled over the period 2006−2017. About 24−25% of N and 12−13% of P in feed were retained in the harvest. The N release during 2006−2017 was approximately 65−67% of the N intake, while P release was 40−42%. Annual N release from mariculture fish production increased from 0.2 to 0.4 Mt between 2006 and 2017 (<one-third of the N release by freshwater aquaculture), while the annual P release increased from 0.03 to 0.06 Mt during 2006−2017 (<44% of the P release by freshwater aquaculture). Between 2016 and 2017, there was an increase of the average annual nutrient release per tonne of mariculture fish production (excluding plants) from 19 to 23 kg of N and from 2.9 to 3.4 kg of P (both N and P release was <44% of the equivalent for freshwater aquaculture). The calculated molar TN/TP ratio of nutrients released to marine environments was about 15:1. The production of all mariculture groups continuously increased during 2006−2017 (5% per year for total mariculture, but with much more rapid growth of the production of carnivores and crustaceans). The total N and P release by carnivores, bivalves, and crustaceans increased less rapidly than their production, while the nutrient release by gastropods increased more rapidly than the production.

Filter-feeding bivalves had a large contribution to the total nutrient release by mariculture (27−34% for total N and 28−35% for total P; 16−21% for dissolved N; and 19−25% of dissolved P) (Figure 5; Table S6). Annual N and P intake in seston increased rapidly (for N from 0.11 to 0.16 Mt, and for P from 0.015 to 0.022 Mt between 2006 and 2017), and ∼32% of N and 16% of P intake were retained in bivalve production.


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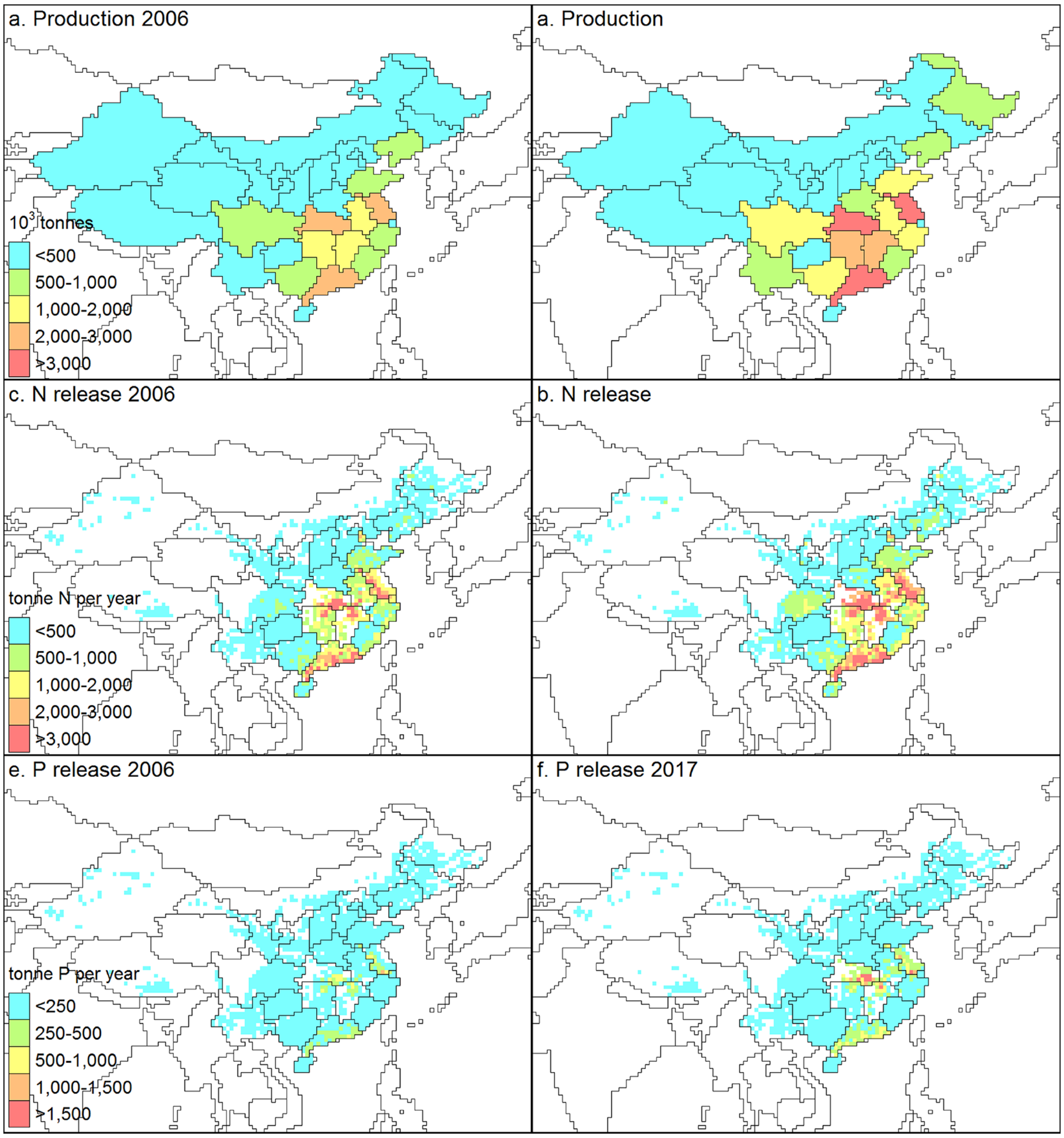


**Figure 4.** Allocation of China Mainland freshwater aquaculture production and associated nutrient release in 2006 and 2017: (a) production in 2006, (b) production in 2017, (c) N release in 2006, (d) N release in 2017, (e) P release in 2006, and (f) P release in 2017. Data for Taiwan are not included in the provincial aquaculture production data.

N release increased from 0.07 to 0.11 Mt during 2006−2017, and that of P from 0.012 to 0.017 Mt. The nutrient release per tonne of bivalve production was about 8 kg of N and 1 kg of P.

Large proportions of N (~80% of feed N intake) and P (~82%) were released from carnivore finfish systems with an estimated N release per tonne of carnivore production of 109−114 kg and P release of around 17−18 kg per tonne carnivore production (Figure 5; Table 1). Their annual production and nutrient intake and release more than doubled during 2006−2017.

The proportion of crustacean production in total mariculture was less than 10% during 2006−2017 (Figure 5; Table 1), but their nutrient intake from feed accounted for 34−38% (N) and 62−65% (P) of the total nutrient intake, while their proportions of total nutrient release from Chinese mariculture fish production were >24% for N and >26% for P. The nutrient release to surface water from crustacean production for N (61 to 58 kg per tonne) and P (9.9 to 9.5 kg per tonne) declined. Nutrients retained in the product accounted for approximately 25% of N and 10% of P in feed. Ammonia volatilization and denitrification from the marine ponds increased from 8 to 16 kt N per year during 2006−2017, which was similar to that from freshwater ponds. The production of gastropods was about 2% of the total mariculture production during 2006−2017, and their proportions of total nutrient release from Chinese mariculture fish production were 7−11% for N and 3−5% for P.

In 2006, the largest part of China's mariculture production was in Shandong, Fujian, and Guangdong with annual production >2 Mt (Table S5; Figure 6; see the coastal areas of the Bohai Sea, northern Yellow Sea, southern East China Sea, and northeastern South China Sea). In 2017, four provinces had an annual production >2 Mt (Shandong, 25% of China's production; Fujian, 19%; Guangdong, 17%; Liaoning, 15%). Shandong and Fujian had production of even >3 Mt per year in 2017 (Figure 6).

The largest estimated N and P intakes in feed in 2006 were in Guangdong, Shandong, and Fujian (Table S5). Provincial



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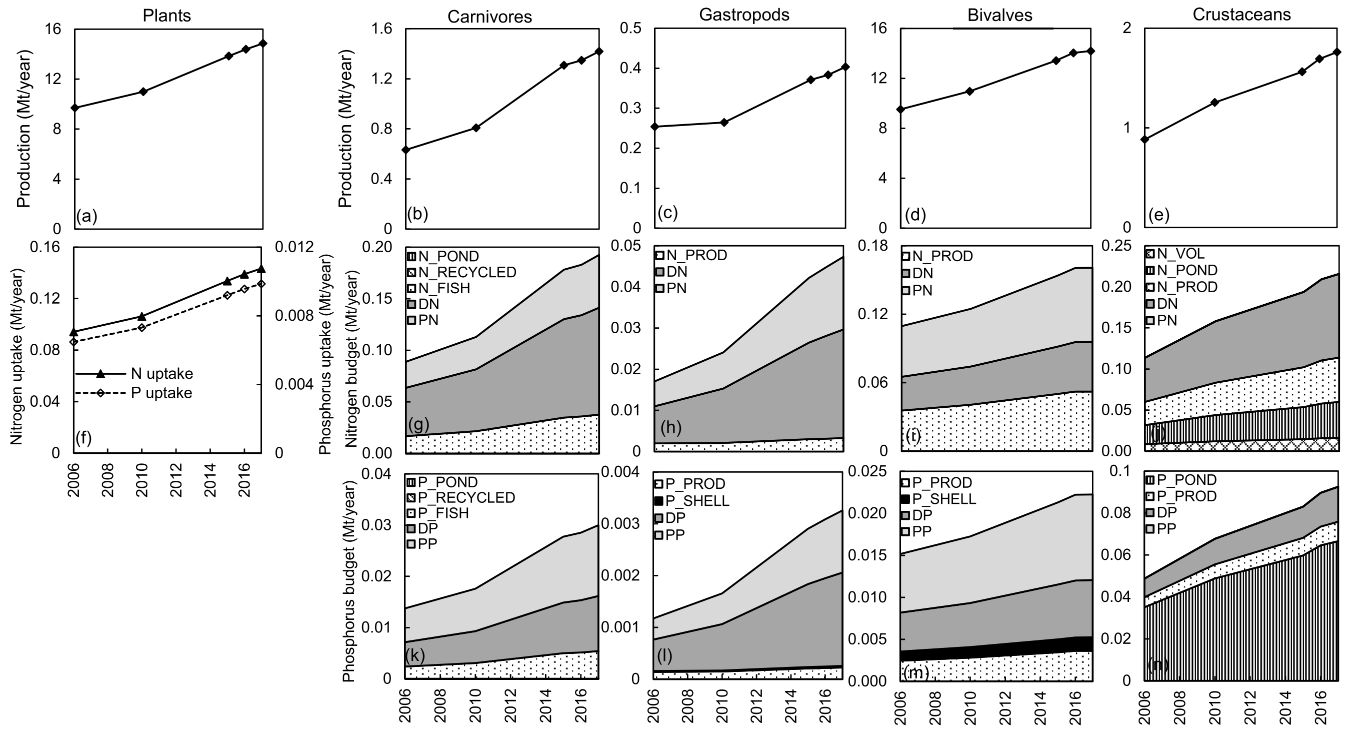


**Figure 5.** Aquatic plant, finfish, and shellfish aquaculture production and associated nutrient budgets in Chinese mariculture production during 2006−2017. (a−e) Production for (a) plants, (b) carnivores, (c) gastropods, (d) bivalves, and (e) crustaceans. Nutrient budgets: (f) nitrogen and phosphorus uptake by aquatic plants; (g−j) nitrogen budgets for (g) carnivores, (h) gastropods, (i) bivalves, and (j) crustaceans; (k−n) P budgets for (k) carnivores, (l) gastropods, (m) bivalves, and (n) crustaceans. Production data for China Mainland are from China Fishery Statistical Yearbook.[28] Provincial total production data and the nutrient budgets (N in feed, harvest and N and P release to surface waters) are in Table S5. Data for Taiwan are not included in the aquaculture production data.

distributions of N and P in the products and nutrients released to surface water were consistent with those of the nutrients in feed. The largest nutrient release is in Guangdong, Fujian, and Shandong in 2017 (Figure 6). In these provinces, carnivore fish are responsible for 40% of the N and 42% of the P release, and bivalves are responsible for 33% of the N release and 34% of the P release.

## 4. DISCUSSION

**4.1. Composition of the Production.** China's freshwater aquaculture production accounted for 66% of the global freshwater production in 2006, and the proportion declined to 59% in 2017; meanwhile, the percentage of freshwater production in global aquaculture production was 44% in 2017.[1] In China, mariculture accounted for 52−55% of the total aquaculture production during 2006−2017, which is similar to the global 54−56%.[1] Although China's mariculture and freshwater production were at the same level, their compositions were different. In mariculture production, plants accounted for 45−46% in China and 45−54% globally and bivalves occupied the second largest fraction both in China (44−45%) and the world (27−35%) during 2006−2017. The fact that bivalves (with a large weight fraction in the shells) are such a large portion of the mariculture production explains why N and P intake, fish uptake,and release are relatively low compared to those in freshwater aquaculture production, which is dominated by finfish. With the rapid increase of shrimp and carnivore finfish production, the nutrient release per ton of production shows an increasing trend (N by 21% and P by 19%) over the period 2006−2017. For freshwater aquaculture production, omnivores accounted for the largest fraction both in China (78−80%) and the world (79−80%) during 2006−2017.

**4.2. Nutrient Release.** Recently, Zhang et al.[5] have estimated that nutrient release from Chinese aquaculture in 2010 was 1.0 Mt of N and 0.17 Mt of P, including 0.18 Mt of N and 0.02 Mt of P from mariculture. Our results for 2010 show a release of 1.0 Mt of N and 0.11 Mt of P from freshwater aquaculture, and 0.27 Mt of N and 0.04 of P from mariculture. Our estimate is remarkably close to and that of mariculture slightly exceeds that of Zhang et al., probably due to differences in the approaches used. Zhang et al.[5] included only fish, shrimps, crabs, and mollusks in the estimation, while many other bivalves, gastropods, invertebrates, reptiles, and crabs in mariculture were ignored. In addition, the nutrient use efficiencies by Zhang et al.[5] were aggregated (shrimps, fish, mollusks, and crabs), which may lead to under- or overestimation when calculating the nutrient release, for example, by ignoring the difference between carnivores that are fed compound feedstuff and omnivore fish feeding on algae. Our results are based on the different feeding practices within ISSCAAP groups.

**4.3. Comparison with Other Nutrient Sources.** In China, annual livestock meat (including pork, chicken, beef, and mutton and goat) production exceeded aquaculture production excluding aquatic plant production by a factor of 5−11 until the mid-1980s (Figure 7[2,4]). The growth in the production of pork, chicken, beef, and mutton and goat meat has been slowing down after 2000 (Figure 7). In contrast, China's total aquaculture production has been continuously increasing since 1950 and growth has been accelerating since 1990 (Figure 1), resulting in a decline in the livestock/



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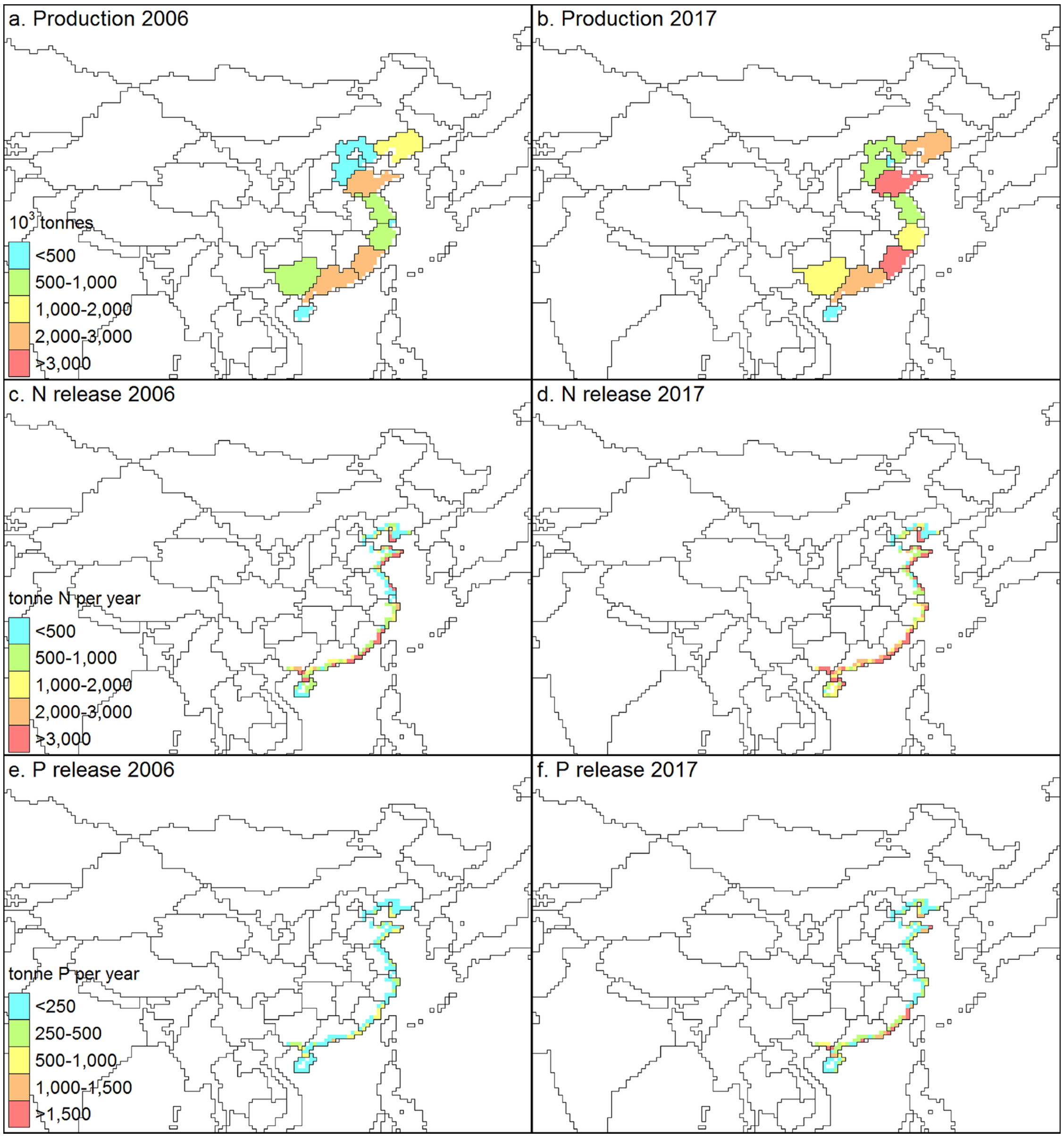


**Figure 6.** Allocation of China Mainland mariculture production and associated nutrient release in 2006 and 2017: (a) production in 2006, (b) production in 2017, (c) N release in 2006, (d) N release in 2017, (e) P release in 2006, and (f) P release in 2017. Data for Taiwan are not included in the provincial aquaculture production data.

aquaculture ratio to 1.7 in 2017. The annual freshwater aquaculture and mariculture production (excluding plants) were 29 and 18 Mt in 2017, respectively, and exceeded the chicken production of 13 Mt per year. Total aquaculture production excluding aquatic plants was of the same order as pork production of 55 Mt (Figure 7). The nutrient excretions by chickens were 4.7 Mt of N and 0.9 Mt of P in 2017, and for pigs, the nutrient excretions were 7.7 Mt of N and 1.3 Mt of P (based on Bouwman et al.[31]). In 2017, the nutrient excretions from China's total aquaculture (i.e., 3.4 Mt of N and 0.7 Mt of P) are currently of the same order of magnitude.

Annual nutrient discharge from point sources in China (i.e., direct discharge and outflow from wastewater treatment plants) was 2.6 Mt of N and 0.4 Mt of P in 2010,[32] which is 16% of total N delivery from all sources (17 Mt per year in 2010) and 25% of total P (1.7 Mt per year in 2010) delivery to surface water in China.[33] Our estimates for nutrient release from freshwater aquaculture in China (1.0 Mt of N and 0.11 Mt of P) into surface water in 2010 make up 6% of total N and 7% of total P delivery obtained from Beusen et al.[33] For some provinces, the nutrient contribution from aquaculture is much higher, for example, Jiangsu (19% of total N and 25% of total P delivery), Hubei (16 and 20%), Tianjin (18 and 14%), Guangdong (14 and 21%), and Anhui (12 and 18%).

**4.4. Comparison with River Export.** The estimated nutrient export by the Yangtze River to the East China Sea and Yellow Sea is 5.9 Mt of N and 0.4 Mt of P for 2010.[34] Our results show that nutrient release from freshwater aquaculture in all provinces that are (partly) drained by the Yangtze River were 0.5 Mt of N and 0.1 of Mt P in 2010. Accounting for 40% retention,[33] which implies that freshwater aquaculture contributes ca. 5% of N delivery and 9% of P delivery in the Yangtze River Basin. The Pearl River with the second largest water discharge in China was estimated to deliver approx-


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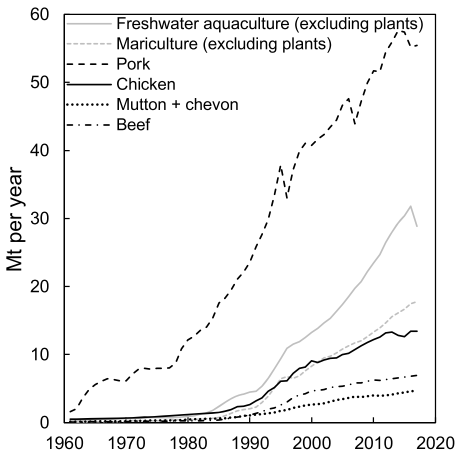


**Figure 7.** China's livestock and aquaculture production excluding the production of aquatic plants for 1960−2017. Production data are from FAO[2,4] and China Fishery Statistical Yearbook.[28]

imately 0.6 Mt of N and 0.02 Mt of P in 2005.[35] Nutrient release from freshwater aquaculture (0.2 Mt of N and 0.02 of Mt P) in all provinces crossed by the Pearl River would represent 19% of river N delivery and 53% of P delivery in 2006. Despite unavoidable overestimation of nutrient release from aquaculture in the Pearl River Basin due to the inclusion of all freshwater aquaculture in provinces crossed by these rivers, this comparison shows that contributions of freshwater aquaculture are considerable.

Nutrients from Chinese mariculture in different coastal provinces are released in different coastal seas (Figures 6, 8, and S1). The Yellow River exported 71 kt of dissolved inorganic N and 0.45 kt of dissolved inorganic P into the Bohai Sea in 2005,[36] which is comparable to nutrient release (54 kt of N and 9 kt of P) from mariculture in the coasts of the Bohai Sea in 2017 (Figure 8). N and P released by mariculture in the South China Sea were 194 and 30 kt in 2017, which were 34 and 124%, respectively, of the nutrients from the Pearl River.[35] In 2017, nutrient release by mariculture in the East China Sea and Yellow Sea was 3% of the N and 6% of the P export from the Yangtze River.[34] While these nutrient contributions from mariculture to Chinese seas are significant compared to the riverine export, the regional impact could be even more prominent as China's mariculture is strongly concentrated in certain provinces, such as Shandong, Fujian, Guangdong, and Liaoning (Figure 6), and within these provinces in sheltered coastal areas. With the expected rapid development of China's mariculture in the future, their nutrient contributions will probably be growing.

The nutrients from freshwater aquaculture that are exported by rivers together with those from mariculture show that assessments of the causes of HABs should include aquaculture. Evidence has shown that the coastal eutrophication situation in Chinese seas worsened rapidly from the late 1980s with increasing nutrient and chlorophyll *a* concentrations, and the numbers of red tides were also observed to increase from 2 to over 70 in the early 2000s and maintained high over the recent decade.[37] The eutrophic area in Chinese seas reaches up to 60 560 and 95 210 km$^2$ in the summer and autumn of 2017, respectively.[38] Based on the increasing frequency, extent, number of locations, and toxicity and damage caused by HABs, the assimilative capacity of the coastal seas of China may already be exceeded. It is therefore urgent to assess nutrient release from aquaculture in more detail and analyze future scenarios, including alternatives for current aquaculture systems such as integrated aquaculture or off-shore production systems.

**4.5. Limitations and Uncertainties.** The nutrient budget model used for aquaculture has many limitations and uncertainties. Sensitivity analysis to variation of modeled nutrient release to variation of a list of model parameters showed that the most uncertain ones are feed conversion efficiencies, apparent digestibility of N and P in compound feed, and parameters describing the feed conversion in omnivore species.[6,7] These parameters need further study and require validation with local information on, for example, feed conversion ratios for different feedstuff and apparent digestibility of feed, local management, such as fish species, feed rations, animal manure and fertilizer use, home-made feed composition and that of compound feeds, as well as environmental conditions such as water temperature. Despite these limitations, it is surprising how close our model-based estimates are to the study of Zhang et al.,[5] who examined the nutrient concentrations in the water and sediments of aquaculture systems and compared these values to data from reference regions without aquaculture pollution. Data on China's aquaculture are, however, limited, especially before 2006, there are important gaps that make estimates before that year very difficult.

Nevertheless, in the provinces where aquaculture has already made significant progress (Guangdong, Shandong, Hubei, Fujian, etc.) or in the provinces where aquaculture is at the initial stage but is expected to increase (e.g., Hebei and Zhejiang), nutrient exports from aquaculture should be given more attention. Since treatments with the nutrients released

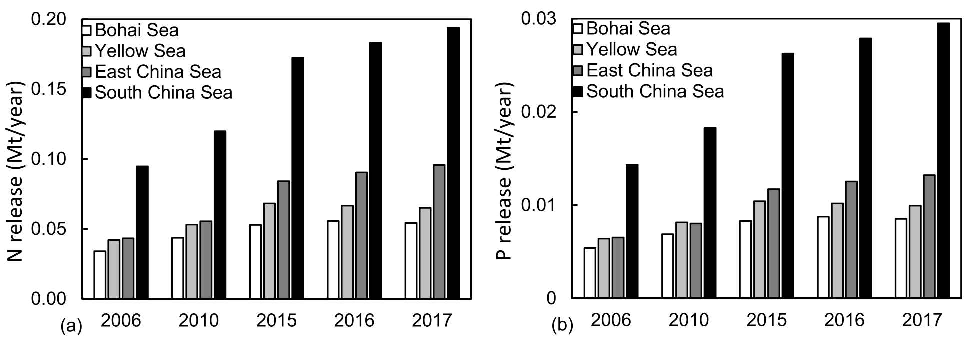


**Figure 8.** (a) Nitrogen and (b) phosphorus release from mariculture into Chinese seas during 2006−2017.



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from aquaculture can require very high costs and technology,[39] reducing nutrient release is preferentially recommended, including increasing the feed efficiency and nutrient recycling within aquaculture system and adopting integrated multi-trophic aquaculture systems.[12,39,40] Furthermore, food composition might be considered to convert to a lower priority of aquatic fish products to feed the increasing, large population.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b03340.

(i) Introduction (docx). (ii) China's aquaculture production data as model input; production and nutrient budgets due to freshwater aquaculture and mariculture in different provinces of China (csv). (iii) The ISSCAAP groups and species included; table and figure descriptions; China's aquaculture production during 2006–2017; data exceptions and their estimation approaches; water bodies distinguished in GLWD for freshwater aquaculture allocation; allocation procedure of aquaculture production and N and P emissions to surface water; production and nutrient budgets of China's freshwater crustaceans, bivalves, and gastropods during 2006–2017; production and associated nutrient release due to finfish and shellfish aquaculture; and Chinese map with provinces and seas (pdf) (ZIP)

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### Notes

The authors declare no competing financial interest.

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## ■ NOTE ADDED AFTER ASAP PUBLICATION

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